

# The growth of the nuclear black holes in submillimetre galaxies

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## ABSTRACT

We show that the ABC scenario we proposed for the co-evolution of spheroids and QSOs predicts accretion rates and masses of supermassive black holes in submillimetre galaxies in keeping with recent X-ray determinations. These masses are well below the local values as well as those predicted by alternative models. The observed column densities may be mostly due to interstellar medium in the galaxy. The contribution of the associated nuclear activity to the X-ray background is likely negligible, while they may contribute a sizeable fraction of  $\sim 10$  per cent to hard X-ray cumulative counts at the faintest observed fluxes.

**Key words:** galaxies: active – galaxies: formation – cosmology: theory – X-rays: galaxies.

## 1 INTRODUCTION

In recent years, many efforts have been devoted to understand the population of high- $z$  galaxies that are detected by submillimetre surveys (SMGs), which could dominate the  $z > 2$  cosmic star formation (SF) and which may pinpoint the major epoch of dust-enshrouded spheroid formation, as suggested by their SF level, high mass fraction, large dynamical mass and strong clustering (Smail, Ivison & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Blain et al. 2004; Greve et al. 2005).

From the theoretical side, the  $\Lambda$  cold dark matter ( $\Lambda$ CDM) cosmology is a well-established framework to understand the hierarchical assembly of dark matter (DM) haloes, but the complex evolution of the baryonic matter remains an open issue, because any simulation must include huge simplifications for its physics. Unfortunately, these simplifications pertain processes which are major drivers of galaxy evolution, such as SF, feedback and nuclear accretion.

The class of computations known as semi-analytical models (SAM) have been extensively compared with a large range of observations at various redshifts. Besides many successes, some difficulties persist in standard SAM, broadly connected with massive galaxies (e.g. the colour–magnitude relation, the  $[\alpha/\text{Fe}] - M$  relation, the statistics of submillimetre (submm) and deep  $K$ -band selected samples: see Thomas, Maraston & Bender 2002; Pozzetti et al. 2003; Somerville 2004; Baugh et al. 2005; Nagashima et al. 2005). However, the general agreement of a broad variety of data with the hierarchical scenario for DM and the fact that the observed number of luminous high-redshift galaxies, while substantially higher than predicted by standard SAMs, is nevertheless consistent with the number of sufficiently massive DM haloes, indicate that we

may not need alternative scenarios, but just some new ingredients or assumptions for visible matter.

In Granato et al. (2001) we suggested that a crucial ingredient to keep account of is the mutual feedback between spheroidal galaxies and the active galactic nuclei (AGN) at their centres, largely ignored by simulations at that time (and often even now). This is despite the fact that since long observations have suggested a connection between SF and AGN activity (e.g. Sanders et al. 1988), the possible importance of the feedback from the central BH has been discussed (among the first were Ciotti & Ostriker 1997; Silk & Rees 1998; Fabian 1999), and its growth has been considered in models for galaxy formation (e.g. Kauffmann & Haehnelt 2000; Archibald et al. 2002). In Granato et al. (2004, GDS04 hereafter) we presented a physical model for the early co-evolution of the two components, in the framework of the hierarchical  $\Lambda$ CDM cosmology and based on the semi-analytic technique. In our model, the SMGs are interpreted as spheroids observed during their major episode of SF. The development and duration of this episode is affected not only by supernova (SN) feedback, but also by the growth by accretion of a central supermassive black hole (SMBH), favoured by the SF itself, and by the ensuing feedback by QSO activity, and completes earlier in more massive objects.<sup>1</sup> Thus the high-redshift QSO activity marks and concurs to the end of the major episode of SF in spheroids.

The scenario discussed by Granato et al. (2001) and GDS04 is based on a circular relationship between SF and AGN activities, which establishes a well-defined sequence connecting various populations of massive galaxies: (i) virialization of DM haloes; (ii) vigorous and rapidly dust-enshrouded SF activity, during which a central SMBH grows; (iii) QSO phase halting subsequent star

<sup>1</sup> Thus we named our scenario the ‘Anti-hierarchical Baryon Collapse’–‘ABC’; from the observational point of view the same phenomenon is now commonly referred to as ‘down-sizing’.

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formation and (iv) essentially passive evolution of stellar populations, passing through an extremely red object (ERO) phase. As detailed by GDS04 and Silva et al. (2005), this scenario nicely fits two important populations at high redshift, which are instead problematic for most semi-analytic models (e.g. Somerville 2004): vigorously star-forming, dust-enshrouded starbursts [in practice SMG; stage (ii)] and EROs (stage iv). Also, the local luminosity function of spheroids and the mass function of SMBHs are well reproduced. The general consistence of this sequence with a high-redshift QSO population has been investigated by GDS04, while a detailed analysis will be presented by Lapi et al. (in preparation).

In this Letter we focus on the model behaviour during the SMBH growth in stage (ii), as traced by X-ray observations of submm selected sources. Alexander et al. (2003, 2005a,b) have investigated the X-ray properties of bright SMGs ( $S_{850\mu\text{m}} \gtrsim 4$  mJy), by combining ultra-deep X-ray observations (the 2 Ms *Chandra* Deep Field North) and deep optical spectroscopic data of SMGs. They have found evidence for the presence of mild AGN activity in a large fraction of bright SMGs ( $\sim 50$  per cent) – which in our scheme is the signature of the SMBH growth – that afterwards will quench the SF and cause an almost passive evolution of stellar populations.

Recently, subgrid treatments of SMBH growth and its feedback has been implemented in numerical simulations of DM haloes and large-scale SPH gas dynamics (e.g. Springel, Di Matteo & Hernquist 2005), or in the semi-analytic post-processing of the Millenium DM simulation (Bower et al. 2005; Croton et al. 2006). However, in the latter cases, the feedback role of AGN is limited to the ‘radio mode’, which suppresses cooling flows in clusters at  $z \lesssim 1$ .

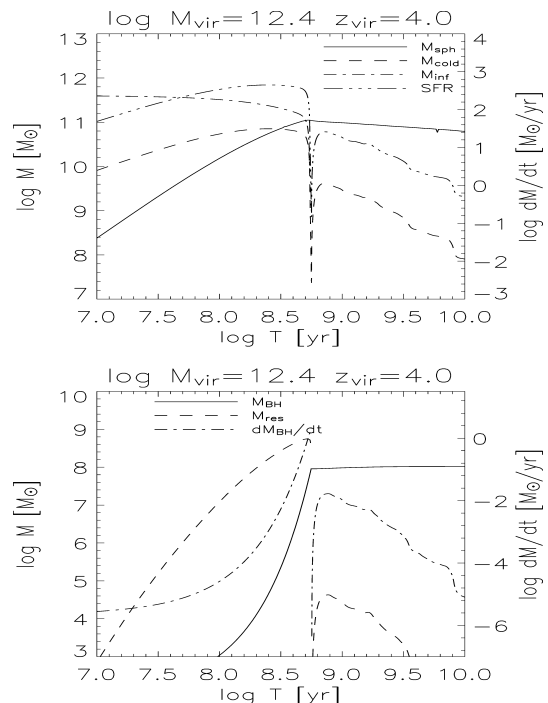
## 2 THE GDS04 MODEL

This Letter is based on the SAM presented by GDS04, which follows the evolution of baryons within proto-galactic spheroids through simple but physically grounded recipes. We provide a qualitative summary of the model, deferring the reader to that paper for details.

The treatment of the statistic of DM haloes essentially follows the standard framework of hierarchical clustering.

During the formation of the host DM halo, the baryons are shock-heated to the virial temperature; this hot gas cools fast, especially in the dense central regions or clumps, and triggers a huge burst of SF. One of the major differences with respect to most semi-analytical treatments of the evolution of visible matter is that in GDS04 cool and collapsing gas forms stars without setting in a quiescent disc.

The SF activity promotes the gathering of a reservoir of gas with angular momentum low enough to allow accretion on to a nuclear SMBH. A plausible process is radiation drag, which ‘naturally’ yields a ratio between SMBH and spheroid mass in keeping with observations. The reservoir gas eventually accretes on to the SMBH, powering nuclear activity. The maximum accretion rate is of the order of the Eddington limit, so that the SMBH mass and the BH activity increases exponentially with time. The energy feedback to the gas by SN explosions and BH activity affects the ongoing SF and BH growth. The two feedbacks have very different dependencies on halo mass and on time since virialization. The SN feedback is an almost immediate consequence of SF and its time-evolution reflects that of SF. It is very effective in low-mass haloes, severely limiting the growth of stellar and SMBH components, but it is of minor importance in most massive galactic haloes; the AGN feedback grows exponentially and is negligible in the first  $\sim 0.5$  Gyr in all haloes, but suddenly becomes very important in DM haloes massive enough to be little affected by SNe feedback. Thus in low-mass haloes, SNe keep the SF at low level, also limiting the growth of the SMBH



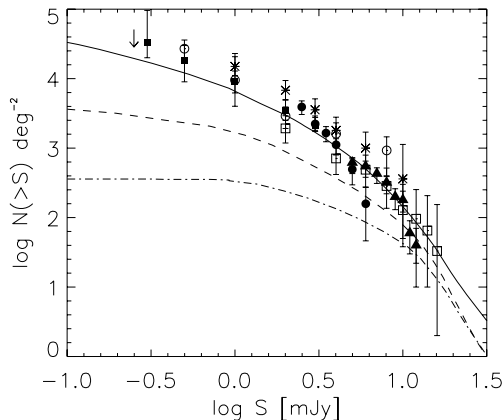
**Figure 1.** Top panel: evolution of the stellar mass, infalling mass, cold gas mass and star formation rate within a typical halo of total mass  $2.5 \times 10^{12} M_{\odot}$ , virialized at a redshift of 4. Bottom panel: evolution of the BH mass, reservoir mass, and BH accretion rates in the same halo. The discontinuity at  $\log T \sim 8.75$  marks the epoch at which the AGN feedback sterilize the system.

and its capability to influence the system. In moderate to high mass haloes (see Fig. 1), the SNe becomes increasingly less effective, the SMBH can grow efficiently and after a time-delay  $\sim 0.5$  Gyr, required by the exponential growth, quenches any further substantial SF, and ultimately its own activity. Since after this point the SMBH is already present at the galaxy centre, any subsequent supplying of gas (e.g. due to merging or accretion of the halo) produces an immediate AGN feedback, and thus is unable to alter substantially the star or SMBH mass: the stellar populations evolve largely in a passive way.

Before the peak of the accretion, the SMBH is likely to be obscured by the surrounding galactic ISM, therefore it could possibly be detected only in the hard-X rays while the proto-galaxy appears as a SMG: *the present Letter is precisely devoted to studying this pre-QSO phase*. Later on, in the proximity of the peak, i.e. when the central SMBH is powerful enough to remove most of the gas and dust from the surroundings, the system will shine as an optical quasar.

## 3 THE ACCRETION OF SMBHs IN SMGs

The GDS04 model predicts the bolometric *intrinsic* time-development of AGN activity in forming spheroids. However, detailed computations on how and when this activity may show up are made extremely uncertain in most electromagnetic bands by environmental effects. For instance, optical-ultraviolet (UV) bands are heavily affected by obscuration due both to the general galactic ISM and to that around the very central region. In the infrared (IR) region, where obscuration is much less of a problem, it is however difficult to disentangle dust emission powered by the AGN from that related



**Figure 2.** Number counts predicted by the GDS04 model for SCUBA sources with accretion rates greater than two interesting thresholds. Solid line: all sources; dashed line:  $\dot{M} > 0.013 M_{\odot} \text{ yr}^{-1}$  ( $L_{\text{bol}} \gtrsim 10^{43} \text{ erg s}^{-1}$ ); dot-dashed line:  $\dot{M} > 0.13 M_{\odot} \text{ yr}^{-1}$  ( $L_{\text{bol}} \gtrsim 10^{44} \text{ erg s}^{-1}$ ). Data from Blain et al. (1999, open circles and upper limit), Eales et al. (2000, filled circles), Chapman et al. (2002, asterisks), Cowie, Barger & Kneib (2002, filled squares), Scott et al. (2002, filled triangles), Borys et al. (2003, open squares).

to SF activity. This is particularly true in our scenario, since the BH growth occurs in an extremely dust-enshrouded environment, without obvious analogue in the local Universe. The situation is more favourable with X-ray photons, especially hard X ones, which are less affected by interactions with the ISM, and are also less likely to be confused with those produced by processes connected with SF, such as X-ray binaries.

Fig. 2 shows the number counts (see e.g. de Zotti et al. 1996 for definitions) for SCUBA sources that host accretion rates on to the central SMBH greater than two interesting thresholds. We predict that about 40 and 15 per cent of SCUBA sources brighter than  $\simeq 5 \text{ mJy}$  have  $\dot{M}_{\text{BH}}$  greater than  $\sim 0.013$  and  $0.13 M_{\odot} \text{ yr}^{-1}$ , respectively (dashed and dot-dashed lines in Fig. 2). With the accretion efficiency assumed to be 0.15 in the model, and adopting a plausible bolometric correction of  $L_{\text{bol}}/L_{\text{X}} [0.5\text{--}8 \text{ keV}] \simeq 17$  (Elvis et al. 1994; Marconi et al. 2004), these values translates to an accretion *intrinsic* luminosity  $L_{\text{X}} [0.5\text{--}8 \text{ keV}]$  of  $\sim 10^{43}$  and  $10^{44} \text{ erg s}^{-1}$ , respectively. These figures compare very well with the findings of (Alexander et al. 2003, see also Alexander et al. 2005a,b). They found that a fraction, 30–50 per cent, of bright ( $\gtrsim 5 \text{ mJy}$ ) SCUBA sources hosts mild AGN activity, with X-ray (0.5–8 keV) *intrinsic* luminosity between  $10^{43}$  and  $10^{44} \text{ erg s}^{-1}$ . This fraction increases to  $\sim 70$  per cent in the radio-selected SMG sample studied by Alexander et al. (2005a,b). However, they caution that this sample may have a higher incidence of AGN activity than the whole SMG population, due to the conditions of radio and spectroscopic identification. Overall, though, the observed high fraction of SMGs which harbour mild AGN activity indicates that they are accreting constantly, hence supporting the picture presented here.

#### 4 ESTIMATES OF COLUMN DENSITIES

According to our interpretation, the moderate AGN activity revealed by X-ray observations in many bright SCUBA sources corresponds to the build-up by accretion of the central SMBH, induced by star formation, and well before the bright QSO phase that causes the end of the major epoch of star formation in these objects.

Alexander et al. (2003, 2005a,b) derive, from the fitting to the X-ray spectra, a column density to the central AGN in the range

$N_{\text{H}} \sim 10^{20}\text{--}10^{24} \text{ cm}^{-2}$  (with most sources showing  $N_{\text{H}} \gtrsim 10^{23} \text{ cm}^{-2}$ ) and a column-density distribution roughly similar to that found for nearby AGN. Hints on the presence of even Compton-thick absorption in these sources are given by the  $\sim 1 \text{ keV}$  equivalent width Fe K $\alpha$  emission line seen in the composite X-ray spectrum of the most obscured objects in their sample.

It is interesting to note that, according to our model interpretation, the values of column densities to the nucleus could be dominated by the general ISM of the galaxy alone, rather than by an obscuring torus such as those invoked by unified models for broad- and narrow-lined AGN. Indeed, during the bright SCUBA phase and after a SMBH sufficiently massive to explain the observed intrinsic X-ray luminosities has developed (i.e. BHs with mass in the range  $M_{\text{BH}} \simeq 5 \times 10^5\text{--}10^7 M_{\odot}$  have accretion rates  $\dot{M}_{\text{BH}} \simeq 0.01\text{--}0.1 M_{\odot} \text{ yr}^{-1}$ , see Fig. 2), the gas mass in galaxies with  $S_{850 \mu\text{m}} \geq 5 \text{ mJy}$  (corresponding to  $M_{\text{vir}} \gtrsim 2 \times 10^{12} M_{\odot}$ ) is usually enough to produce column densities to the nucleus of  $N_{\text{H}} \gtrsim$  a few  $\times 10^{23}$  to a few  $\times 10^{24}$ . This is the case if the radial density distribution is sufficiently centrally concentrated, such as a typical King profile with core radius  $\sim 0.3\text{--}1 \text{ kpc}$  (depending on the galaxy mass). However, the precise value of  $N_{\text{H}}$  is strongly dependent on the assumed profile. A lower limit is obtained if the gas is more or less uniformly distributed in the galaxy. In this case,  $N_{\text{H}}$  would drop by 2–3 orders of magnitude, becoming almost negligible with respect to the observed estimates. Note also that the observed values of  $N_{\text{H}}$ , when translated to optical dust absorption by adopting a standard conversion factor ( $N_{\text{H}} \sim 1.5 \times 10^{21} A_{\text{V}}$ ), yield large values, consistent with the fact that these AGN are unseen at optical wavelengths.

In GDS04 the fuelling of the central BHs in SMGs takes place in two steps: (i) a low-angular momentum gas reservoir is formed, then (ii) that reservoir is accreted on to the BH in a time-scale set by the Eddington limit (see Section 2). Thus the growing BHs may also be hidden by the reservoir. If we assume that its gas is distributed within a region of  $\sim 100\text{--}200 \text{ pc}$ , i.e. the typical size of the dusty torii that explain the IR SED of type 1 and 2 AGN (e.g. Granato & Danese 1994), then the values of  $N_{\text{H}}$  that we obtain during the SMG phase are between a few  $10^{23}$  to  $10^{26} \text{ cm}^{-2}$ . These values are again compatible with the observational estimates. If the matter is distributed around the BH in a toroidal-type shape, rather than completely surrounding it, the visibility of the central AGN would depend also on the distribution of the aperture angles.

#### 5 THE MASSES OF SMBHs IN SMGs

Recently, some hydrodynamic simulations of galaxy major mergers incorporated, with sub-grid approximations, the growth of the black hole and its feedback on the evolution of the system (e.g. Di Matteo, Springel & Hernquist 2005; Springel et al. 2005). As noticed by Alexander et al. (2005a,b), the black holes of the most massive galaxies in these simulations (which may represent the SMGs in this merging scenario) are up to an order of magnitude more massive than those estimated in SMGs, under the assumption of Eddington-limited accretion, and confirmed by the relative narrowness of broad emission lines detected in some sources. These estimates are instead in good agreement with our predictions, at least on average.

This basic difference is due to the fact that in the merging scenario the most active SF phase, corresponding to the final merge, is preceded by a long  $\sim 1\text{-Gyr}$  phase of disturbance which causes a substantial growth of the SMBH. As a result, when the final merge

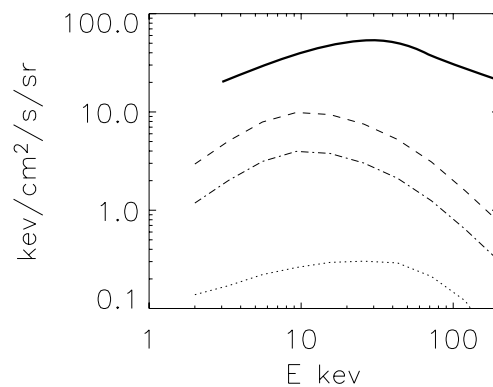
occurs, the SMBH is already massive enough to immediately accrete all the matter funnelled in its proximity. Conversely, in our scenario the SFR reaches levels close to the peak value on a short time-scale ( $\lesssim 0.1$  Gyr), and remains at these levels until the Eddington-limited growth of the SMBH, which requires  $\sim 0.5$  Gyr to build up the final mass, ultimately sterilizes the system (see Fig. 1). In this case, then, the SMBH is well below its final mass during most of the ‘burst’.

Borys et al. (2005) have investigated the relationship between the SMBH and stellar mass in SMGs,  $M_{\text{BH}}/M_*$ , finding values that are 1–2 orders of magnitude smaller than those of local spheroids with similar masses. They notice that this result may be affected by a few assumptions, and their sample has a modest dynamic range ( $\log M_* = 11.4 \pm 0.4$ ). In our scenario we would expect, during the SMGs phase, an average  $M_{\text{BH}}/M_*$  of the same order of magnitude as that found by Borys et al., but with a larger dispersion. The observed lack of detected objects with smaller values may be easily accounted for by selection effects, due to the low accretion rate (and possibly high obscuration) of AGN activity in the very early phases. As for the lack of observed SMGs with  $M_{\text{BH}}/M_*$  closer to the local value, the more obvious possibility is that an important ejection of the dusty ISM begins somewhat earlier than is predicted by our schematic model, causing a decrease of the submm flux below the current sensitivity in the last 3–4 e-folding times of SMBH growth before the maximum. This would not affect the good match with observed SMGs counts too much, while explaining the lack of submm sources with more evolved SMBH. Note also that the reservoir mass increases steadily up to very close to the maximum of the accretion rate (see Fig. 1). If this reservoir were responsible for most of the obscuration (see Section 4), the last e-folding times of the SMBH growth before the optical QSO shining could be undetectable even in the X-ray band, because the increasing optical depth would overwhelm the increasing intrinsic power. Deeper submm and X-ray data will clarify this issue.

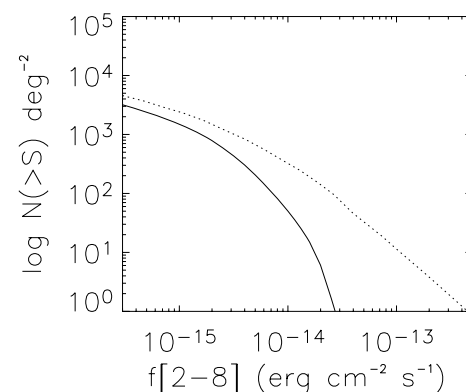
## 6 X-RAY BACKGROUND AND COUNTS

A detailed prediction of the contribution of forming spheroids and SMBH to X-ray counts and background (XRB), in the context of our model, is a complex issue, involving assumptions not only of the fraction of AGN bolometric luminosity emitted in this spectral region, but also of the (distribution of the) absorbing column densities, which are expected to evolve during the SMBH build-up. As discussed above, we can only attempt an order of magnitude estimate of the range of  $N_{\text{H}}$  values with our model, but these values are in agreement with those found by Alexander et al. (2003, 2005a,b). Thus, to make a crude estimation of the observable X-ray emission, we assume a reference value of  $N_{\text{H}} \sim 3 \times 10^{23} \text{ cm}^{-2}$ , and we use the X-ray SED defined by Ueda et al. (2003) for AGN with  $\log N_{\text{H}} = 23.5$  for our mock objects, which includes a Compton reflection bump, low energy absorption and exponential cut-off at 500 keV.

Growing AGN in SCUBA sources may contribute about 20 per cent to the XRB at around 10 keV, where the contribution peaks (Fig. 3). If we include only submillimetric sources down to flux limit of  $\simeq 1$  mJy, the contribution decreases by more than a factor 2. These figures should be regarded as upper limits, as we expect a fraction of AGN to be affected by column densities larger than those found by Alexander et al. Assuming a higher value,  $\log N_{\text{H}} = 24.5$ , would cause a sharp drop below 10 keV; the estimate is little affected above this energy, and the contribution decreases here anyway.



**Figure 3.** Predicted X-ray background from growing SMBHs in all forming spheroids (short-dashed line), and from those in SCUBA sources brighter than 1 mJy (dot-dashed line). We adopted  $\log N_{\text{H}} = 23.5$  (see discussion in the text). The dotted line is the estimated contribution from stellar populations computed with GRASIL (Silva et al. 1998, 2003). The data (thick solid line) are those adopted by Ueda et al. (2003).



**Figure 4.** Contribution to the X-ray number counts by growing SMBHs in forming spheroids according to the model (solid line). In the computation we have adopted a reference value of  $\log N_{\text{H}} = 23.5$  (see discussion in the text). The dotted line outlines the observed counts from various sources (Gilli 2003).

The predicted X-ray counts due to growing SMBHs in forming spheroids are shown in Fig. 4, again adopting  $\log N_{\text{H}} = 23.5$ . Using  $\log N_{\text{H}} = 24.5$  instead, the predicted cumulative counts decrease by a factor  $\sim 2$  at the faint end ( $< 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ ), where in any case they could provide a sizeable fraction of sources.

## 7 SUMMARY AND CONCLUSIONS

We added support to the idea that the *mutual* relationship between the formation of spheroids and the AGN activity is a key ingredient that *must* be included into models of galaxy formation. The prescriptions of our ABC scenario (Granato et al. 2001, 2004) lead to predictions that are in general agreement with many observations. Here we concentrated on X-ray properties of SMGs, which support one of its basic ingredients, namely the SF-promoted growth of a SMBH. Constraints on model details in the final phase of this growth are expected from deeper submm and X-ray observations.

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